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The Puzzles of RX J1856.5-3754: Neutron Star or Quark Star?

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We discuss recent Chandra and XMM-Newton observations of the bright isolated neutron star RX J1856.5−3754 and suggest that the absence of any line features is due to effects of a high magnetic field strength ($\sim 10^{13}$ G). Using different models for the temperature distribution across the neutron star surface assuming blackbody emission to fit the optical and X-ray spectrum and we derive a conservative lower limit of the "apparent" neutron star radius of 16.5 km × (d/117 pc). This corresponds to the radius for the "true" (de-redshifted) radius of 14 km for a 1.4 $M_\odot$ neutron star, indicating a stiff equation of state at high densities. A comparison of the result with mass-radius diagrams shows that quark stars and neutron stars with quark matter cores can be ruled out with high confidence.

1. INTRODUCTION

The excellent soft X-ray response of ROSAT pointed and all-sky observations [1] have led to the discovery of eight thermally emitting objects (listed in Table 1) having roughly the size of a neutron star but showing not any radio emission [2].

Among these objects RX J1856.5-3754 is the brightest and thus best qualified for detailed studies aiming at a determination of its radius, surface gravity and gravitational redshift by means of X-ray spectroscopy, allowing to determine the equation of state of matter at supranuclear densities. In this paper, we concentrate primarily on this object and first summarize the main observational facts.

RX J1856.5−3754 (henceforth RXJ1856) was discovered serendipitously in a ROSAT field by Walter et al. [3]. Using the HST Walter & Matthews [4] identified the X-ray source with a faint blue star (V ∼ 26 mag). Its distance and proper motion were measured with HST as well, yielding (117 ± 12) pc and 0.33 arcsec/year, respectively [5,6]. With the VLT van Kerkwijk & Kulkarni [7] found a faint nebula surrounding the point source which has a cometary-like geometry with a 25" tail extending along the direction of motion. None of the X-ray observations revealed any variability on time scales up to ten years. The so far best upper limit of 1.3% (2σ) on periodic variations in the range $10^{-3} - 50$ Hz has been established by Burwitz et al. [8] using a XMM-Newton EPIC-pn observation. Chandra LETG observations with high spectral resolution show a featureless spectrum that can be fit by a Planckian spectrum with a temperature of 63 ± 3 eV [8]. Compared with the optical spectrum which shows a Rayleigh-Jeans slope, the X-ray spectrum is reduced by a factor of ∼ 6. Therefore the overall spectrum of the source has often been described by a two-temperature blackbody model e.g. [8,9,11,13].

A large number of papers have been dealing with the nature of this compact object and the proposed interpretations include almost everything which has ever been discussed in this context, ranging from "normal" neutron stars with a stiff or soft equation of state over neutron stars having a quarks core to bare strange quark stars. In this paper, we show that the observational data require a normal neutron star with a rather stiff equation of state.

2. THE MAGNETIC FIELD STRENGTH OF RX J1856.5−3754

The lack of any significant spectral features in the LETG spectrum excludes magnetic fields of $(1.3 - 7) \times 10^{11}$ G (for electrons) and

Table 1
Parameters of X-ray-dim isolated neutron stars.

Source Name	P (s)	$\dot{P}$ ($s\,s^{-1}$)	L_X ($erg\,s^{-1}$)	kT_{BB} (eV)	d (pc)	Opt. (mag)
RX J0420.0−5022[a]	3.45	–	2.7×10^{30}	44	100	$B > 25.5$
RX J0720.4−3125	8.39	$(3–6)\times10^{-14}$	2.6×10^{31}	85	100	$B = 26.6$
RX J0806.4−4123	11.37	–	5.7×10^{30}	95	100	$B > 24$
1RXS J130848.6+212708	10.31	$<6\times10^{-12}$	5.1×10^{30}	90	100	$m_{50CCD} = 28.6$
RX J1605.3+3249	–	–	1.1×10^{31}	92	100	$B > 27$
RX J1836.2+5925	–	–	5.4×10^{30}	43	400	$V > 25.2$
RX J1856.5−3754	–	–	1.5×10^{31}	63	117	$V = 25.7$
1RXS J214303.7+065419	–	–	1.1×10^{31}	90	100	$R > 23$

[a] Period and temperature from XMM-Newton data (Haberl et al. *in preparation*).

$(0.2 - 1.3) \times 10^{14}$ G (for protons), see Burwitz et al. [10]. This leaves the possibility of a low magnetic field characteristic for millisecond pulsars or a high magnetic field typical for normal pulsars open. Unfortunately, due to the absence of a periodicity the usual estimate of the magnetic field of RXJ1856 based on the rotating dipole model is not possible. Using phenomenological arguments based on the very small pulsed fraction in X-rays and on a comparison with other objects van Kerkwijk & Kulkarni [7] have argued that the star has a relatively low magnetic field of a few 10^{11} G which may be marginally consistent with the absence of proton cyclotron lines. But this is not the only possibility. We estimate the magnetic field making use of the spin-down luminosity $dE/dt \sim 4 \times 10^{32}$ erg/s required for powering the cometary-like emission nebula [7] and of the age of the star ($t \sim 5 \times 10^5$ years) inferred from its proper motion and the distance to its likely birthplace in the Upper Sco OB association [5]: assuming as usual the validity of magnetic dipole braking we find a period of a $\sim$1.8 sec and a magnetic field strength of $\sim 1.1 \times 10^{13}$G. We emphasise that these figures are very similar to those of the second brightest object of this kind, the pulsating source RX J0720.4−3125 (henceforth RXJ0720) whose spectral characteristics are also very similar to those of RXJ1856 (see below). While the estimate of dE/dt may be considered as rather reliable, the age derived from the birthplace argument is not so certain. However, an age of $t \sim 5 \times 10^5$ years (with an uncertainty of a factor of two) is fully consistent with what we know empirically about the cooling of neutron stars. We therefore conclude that the magnetic field of RXJ1856 is probably large, i.e. of the order of $> 10^{13}$ G. To support this, it will be important to exclude the alternative hypothesis of a millisecond pulsar [7,11] by means of a high time resolution observation with XMM-Newton which has already been approved.

3. THE FEATURELESS X-RAY SPECTRUM OF RX J1856.5−3754

The main puzzle of RXJ1856 is the observational fact that its X-ray spectrum is completely featureless. It has been pointed out by Burwitz et al. [8,10] that nonmagnetic photospheric spectra assuming a pure iron composition are incompatible with the measured spectrum because the predicted Fe-L features are not detected with high significance. Even a solar composition model with its small abundance of metals leads to unacceptable spectral fits. Doppler smearing of the spectral lines due to fast rotation does not wash away completely the strongest spectral features [12,13]. On the other hand hydrogen or helium photospheres can be excluded, because they over-predict the optical flux by a large factor [14]. Therefore any nonmagnetic photosphere can be firmly excluded.

As a remedy it has been proposed that the star

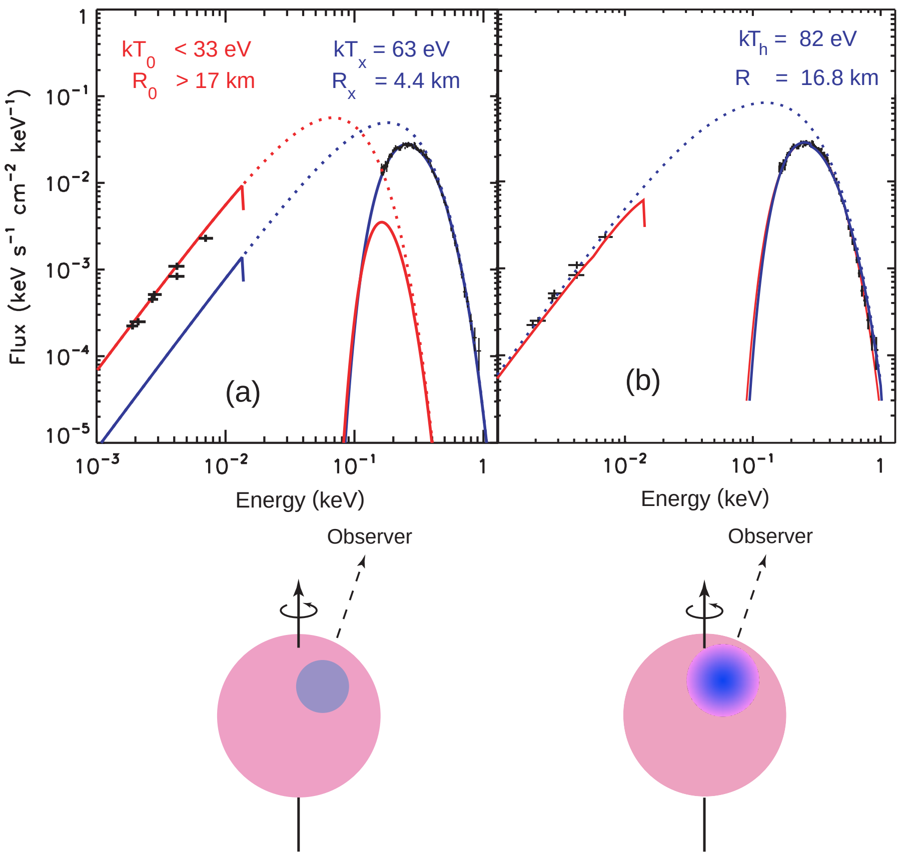

Figure 1. Blackbody fits to the optical and X-ray spectra of RX J1856.5-3754 for a two-component model (a) and a model with a continuous temperature distribution (b).

has no atmosphere but a condensed matter surface [10,15]. Such a surface is expected to be reflective in the X-ray domain [16,17] which could help to explain the low X-ray/optical flux ratio. Condensation of surface matter requires low temperatures and strong magnetic fields. To condense hydrogen at a temperature of $\mathrm{kT} = 63\,\mathrm{eV}$ a magnetic field of $5 \times 10^{13}\,\mathrm{G}$ is required [18]. For iron it is not clear whether a condensate can exist at all. According to Lai [18] the cohesive energy of iron is uncertain, but condensation may occur at $3 \times 10^{11}\,\mathrm{G}$ (at $\mathrm{kT} = 63\,\mathrm{eV}$) while Neuhauser et al. [19] conclude that iron cannot condensate. Another problem is that the optical properties (the reflectivity depending on photon energy, polarisation and magnetic field angle) of a condensed matter surface have not been calculated taking into account the effects of atomic energy levels and of the solid state structure. Simplified models which calculate the reflectivities of a highly magnetized, high density electron plasma have been performed by Lenzen & Trümper [16], Brinkmann [17], Zane et al. [20] and Turolla et al. [15]. They yield X-ray reflectivities of typically $10-30\,\%$ which smoothly depend on frequency. Close to the cyclotron frequency $\sim 50\,\%$ is reached. We note that this is not sufficient to fully explain the reduced X-ray flux which would require a reflectivity of $\sim 85\,\%$.

Another possibility to suppress atomic line features is to employ super-strong magnetic fields. The energy levels for iron atoms in strong mag-

netic fields (10^{13} G) calculated by Neuhauser et al. [19] are pretty much smeared over the entire LETG energy range and have a spacing of $50-100$ eV. That could be easily resolved by the LETG (resolution <1 eV). However, the individual levels show a $B^{0.4}$-dependence and therefore a smearing is expected to take place if the flux is integrated over the whole stellar surface. For a dipolar field with a factor of two variation of the magnetic field between pole and equator the lines would be broadened by $80-300$ eV . Thus it is plausible, that the combination of a dense level structure of the magnetic atoms with a dispersion of the magnetic field produces a spectrum which appears as a continuum seen with the LETG. We believe that this is the most promising model for explaining the featureless X-ray spectrum, but it has to be confirmed by detailed calculations.

4. THE ABSENCE OF PERIODIC VARIATIONS OF RX J1856.5−3754

The upper limit of 1.3 % for the amplitude of periodic variations requires a pretty good alignment between the rotational axis and the line of sight if the overall spectrum is represented by a two-temperature blackbody model [12]. We note that this constraint can be somewhat (but not fully) relaxed if the X-ray flux were reduced due to reflection effects because the size of the X-ray emitting spot would be increased. Another possibility is that the rotational frequency of the neutron star is larger than the present limit of observations (50 Hz). This will be checked by a forthcoming accepted XMM-Newton observation with the EPIC pn-CCD camera in using its high time resolution mode.

5. COMPARISON WITH RELATED OBJECTS

(1) RX J0720.4-3125: The second brightest of the sources listed in Table 1 is RXJ0720 which looks like a twin of RXJ1856 in many respects: It was discovered in the ROSAT all sky survey and has a (blackbody) temperature of $kT = 79 \pm 4$ eV. The X-ray source was optically identified with a $B = 26.5$ mag object by Motch & Haberl [21] and Kulkarni & van Kerkwijk [22]. The optical to X-ray flux ratio is about 5. RXJ0720 shows X-ray pulsations with a period of 8.3914 sec and a pulsed fraction of ~ 10 % [23]. A timing analysis including all available archival and new ROSAT, Chandra, and XMM-Newton data indicates that the source is spinning down with a rate of $dP/dt \sim 10^{-14}\,s\,s^{-1}$ [24]. When interpreted in terms of magnetic braking this results in a magnetic field of $B \sim 2 \times 10^{13}$ G.

A broad spectral feature at ~ 270 eV was found in the EPIC-pn-spectra and when interpreted as a proton or iron cyclotron resonance yields a magnetic field strength of $\sim 5 \times 10^{13}$ G and $< 2.5 \times 10^{13}$ G, respectively, consistent with the value derived from the spin down [25].

(2) 1RXS J130848+2127 (=RBS1223): A strong broad band absorption feature was detected in the spectrum of this 10.31 s pulsar, with a similarly inferred magnetic field strength of $(2-6) \times 10^{13}$ G [26]. This pulsar shows a double peaked pulse profile.

The similarities of these three sources strengthen the case of a strong magnetic field of RXJ1856. Actually the main difference between them may be in the configuration of spin axis, magnetic axis and the line of sight.

6. MODIFICATION OF THE PLANCKIAN SPECTRUM

Yet another similarity between these sources regards the shape of the X-ray continuum. Although in the cases of RXJ1856 and RXJ0720 a Planckian distribution yields a very good fit to the data a modified Planckian of the type $E^a \times$ Planckian fits even somewhat better. This has been first discussed by Burwitz et al. [10] for RXJ1856 for which $a = 1.28 \pm 0.30$, but also applies to RXJ0720 which has $a = 0.98 \pm 0.30$. In compensation for the steeper continuum the interstellar column densities n_H and temperatures of RXJ1856 are reduced by ~ 50 and ~ 10 %, respectively. We note that such a broad band modification does not affect the discussion of the absence of (narrow band) line features. But it may be connected with an energy dependent reflection coefficient of the emitting surface.

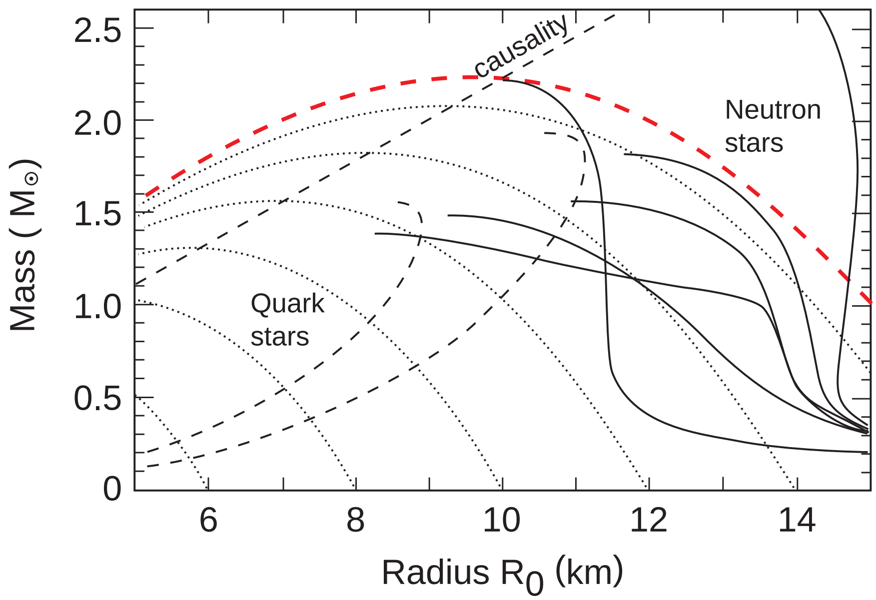

Figure 2. The mass-radius relations for various equations of state for the nuclear matter according to [9]. The thick dashed curve (red) represents the apparent neutron star radius derived from both the two-component and continuous temperature blackbody models.

7. A LOWER LIMIT TO THE RADIUS OF RX J1856.5−3754

In the absence of any spectral features the determination of the neutron star radius hinges on the distance, for which we adopt $d = 117\,\mathrm{pc}$ [5,6]. In the following we first use the parameters of a two component blackbody model for the optical and X-ray spectrum of RXJ1856 (Burwitz et al. [8]) which is shown in Fig. 1a. The blackbody radius and temperature of the X-ray emitting hot spot derived from the Chandra LETG spectrum are $R_X = 4.4\,\mathrm{km}$ and $kT_X = 63\,\mathrm{eV}$, respectively. The optical spectrum is interpreted as the sum of the Rayleigh-Jeans spectra of both the hot and the cool component. This fixes $(R_{opt})^2 \times T_{opt} + (R_X)^2 \times T_X = 33\,\mathrm{eV} \times (17\,\mathrm{km})^2$. The condition that the optical spectrum of the cool component does not show up as a deviation in the X-ray spectrum limits the corresponding temperature to $kT_{opt} < 33\,\mathrm{eV}$ at the $3\,\sigma$ level [8]. Using these figures we find for the radius of the neutron star $R = (R_{opt}^2 + R_X^2)^{1/2} > 16.5\,\mathrm{km}$ $(3\,\sigma)$.

As an alternative we discuss a model with a continuous temperature distribution (c.f. Fig. 1b of the form

$$T = T_{hot} \times \left[1 + \left(\frac{\theta}{\theta_0}\right)^{\gamma}\right]^{-1} \qquad (1)$$

The best fit to both the optical and the X-ray spectrum yields a central temperature of the hot spot $T_{hot} = 82\,\mathrm{eV}$, an angular size of the hot spot $\theta_0 = 40°$ and $\gamma = 2.1$. In this case the neutron star radius is 16.8 km. We note that such hot spots may be caused by an anisotropic heat transport in strong magnetic fields ($> 10^{13}$ G [27]) or by polar cap heating in a millisecond pulsar [11].

The quoted apparent radii $R = 16.5\,\mathrm{km}$ for the two-component model (Fig. 1a) and $R = 16.8\,\mathrm{km}$ for the continuous temperature distribution model (Fig. 1b) represent rather lower limits since they have been derived under the assumption of blackbody emission. These apparent radii R are related to the true stellar radius R_0 which is usually quoted in the literature by

$$R = R_0(1 - R_S/R_0)^{-1/2} \qquad (2)$$

where $R_S = 2GM/c^2$ is the Schwarzschild radius. For a standard neutron star of 1.4 solar masses the true radii are $R_0 = 14.0$ km (Fig. 1a) and $R_0 = 14.1$ km (Fig. 1b), respectively, and thus considerably larger than the usual standard radius of 10 km. This implies a rather stiff equation of state. We note that the same conclusion was reached by Braje & Romani [12] using a two component model and similar arguments. In order to compare our results in more detail with the predictions of theoretical neutron star models we use the mass-radius diagram given by Pons et al. [9]. This diagram is shown in Fig. 2 to which we have added a curve corresponding to the apparent radius derived in this paper. It is evident that the lower limit represented by the thick dashed curve excludes the quark star discussed in [9] with high significance. It even excludes the quark star models discussed by Schertler et al. [28] which have even smaller radii, as well as neutron stars with strange quark matter cores discussed in the same paper. In view of the small uncertainties in the distance (117 ± 12) pc of RXJ1856 and the fact that the blackbody leads to an underestimate of the emitting area we conclude that this object is a neutron star with a stiff equation of state and that the possibility for a quark star and a quark core star can be ruled out with high confidence.

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